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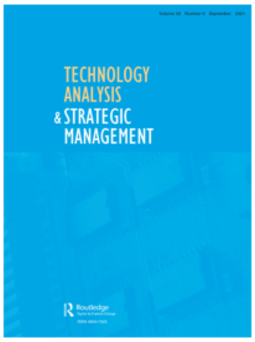

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Asleep at the wheel? Responsible Innovation in quantum computing

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ABSTRACT

Quantum computing is an emerging set of technologies which promise to transform aspects of computing in ways that, though increasingly defined, are still largely theoretical. Responsible Innovation (RI) asserts that technologies with potentially transformative capacity on society should be approached with care and forethought; this paper is based on applying RI in one of the UK's National Quantum Technology Hubs.

Quantum computing is at a key juncture as it emerges from the laboratory to be of interest commercially. This provides an opportunity to observe and influence the trajectory of this technology. Quantum computing is widely envisioned to have major impacts on computing and society; there are, however, great uncertainties about development timescales and the scope and impact of applications.

From experiences with a major quantum computing project in the UK, we discuss the challenges in applying RI to quantum computing. Existing RI practices struggle to address the societal implications of such a complex and innovative technology. We argue that uncovering the visions and sociotechnical imaginaries that inform the development this technology enables RI to make valuable insights into future societal implications of quantum computing. This provides lessons for RI in emerging technologies more widely.

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Responsible innovation; quantum computing; sociotechnical imaginaries

Introduction

The Promethean powers of modern technology are expanding at an ever-increasing rate. Quantum computing promises to be one of these powers. Even if society is not, as some fear, '*asleep at the wheel*' (Khan 2021), experience with other emerging science and technology shows that social control of technologies faces a dilemma: potentially harmful outcomes cannot easily be anticipated and controlled in the earliest stages of development, but it is difficult to change the trajectory later once outcomes are more evident (Collingridge 1980).

How, then, is Responsible Innovation (RI) to understand and react to the choices made available by an emerging technology, when so little can be known about the implications? Despite the profoundly uncertain early stages of emerging science and technology, we believe that it is possible to discern, and potentially to intervene in the *meanings* (van der Burg 2014), visions, and sociotechnical imaginaries (Jasanoff 2015) which drive and shape new technologies.

Quantum computing aims to harness the phenomena of quantum mechanics – such as entanglement and superposition – to do things which cannot be done by current 'classical' (non-quantum)

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computing methods (Montanaro 2016), such as efficient searching through unordered data, optimisation, simulating the behaviour of molecules, and factorisation. Already there is interest in exploiting existing or soon-to-exist devices using quantum methods for applications that can address difficult and useful real-world computing problems (Preskill 2018). Quantum computing in some forms, therefore, is already with us; now is an appropriate moment at which to consider the implications of these new technologies. It is at this stage, when the processes and products are becoming discernible but not yet established, that we can consider what sort of futures we want these new technologies to engender.

This paper draws evidence from interviews and workshops in the application of RI in a major UK project in quantum computing: Networked Quantum Information Technologies (NQIT), one of four quantum technology Hubs in the UK National Quantum Technologies Programme (UKNQTP) (UK Research and Innovation 2021). The process of RI in NQIT included one-to-one semi-structured interviews with key researchers and directors of NQIT, a series of workshops at NQIT events and other UKNQTP Hubs, and case studies of quantum machine learning and defence and national security implications of quantum technologies (Inglesant, Hartswood, and Jirotka 2016; Inglesant, Jirotka, and Hartswood 2018).

Responsible Innovation

There are several currents and themes in Responsible Innovation (RI) (also sometimes known as Responsible *Research and* Innovation (RRI); for a useful discussion of these two linked discourses, see Owen and Pansera (2019)). RI emphasises proactive and anticipatory responses, in contrast to retrospective risk-based regulation of the outcomes. RI proposes '*a transparent, interactive process*' to address '*the (ethical) acceptability, sustainability, and societal desirability of the innovation process and its marketable products … to allow a proper embedding … in our society*' (von Schomberg 2013).

One approach to RRI has been developed by the European Commission and focusses around five themes: public engagement, open access, gender equality, ethics, and science education, plus, in various versions, governance and institutional change.[1]

In the UK, the Engineering and Physical Sciences Research Council (EPSRC) has adopted the AREA Framework - Anticipate, Reflect, Engage, Act,[2] based on work by Stilgoe, Owen, and Macnaghten (2013) (Table 1). Jirotka et al. (2017) added a second range of attributes: the '4 P's': the Products, Processes, People, and Purpose, to articulate its practical application as the AREA Plus Framework.

Fundamentally, RI questions the framings which surround science and innovation (Williams and Edge 1996; Grunwald 2011; Stilgoe and Guston 2017; Özdemir 2019). We draw on these insights to uncover attributed meanings and to dig more deeply into opportunities for assessment and intervention (Williams 2006). We consider the '*sociotechnical imaginaries*' (Jasanoff 2015) which shape actually-existing and still-emerging technologies, and show how, by reflecting on these, the trajectory of *innovation* may be changed.

These visions and imaginaries are not fixed but are continually negotiated in dialogue — a dialogue in which some voices will be heard more loudly than others. Certain technologies, because of their perceived immense potential, come to be viewed in the context of national strategy and as part of '*the design and fulfilment of nation-specific … projects*' (Jasanoff and Kim 2009) in the national

Table 1: The AREA Framework

Anticipation	Anticipation means preparedness rather than prediction in the face of novel technologies (Collingridge 1980; Guston 2014).
Reflection	Holds a mirror to value systems, assumptions and framings that inform our own activities; questions the 'moral division of labour' (Swierstra and Rip 2007).
Engagement	'Opening up' (Stirling 2008) processes of research and innovation to wider participatory deliberation.
Action	'Responsiveness' (Stilgoe, Owen, and Macnaghten 2013) is the capacity to change trajectory where necessary; for example, midstream modulation (Fisher, Mahajan, and Mitcham 2006), or Stage-Gates (Stilgoe, Owen, and Macnaghten 2013).

collective imagination. Quantum computing is particularly rich in such visions. Indeed, the work on which this paper is based is part of a national strategy (UK National Quantum Technologies Programme Strategic Advisory Board 2015a), geared towards 'a new era for the UK' and promising '*the next generation of products with exciting and astounding properties that will affect our lives profoundly*'.

The emergence of 'revolutionary' new technologies is often accompanied by claims about their transformatory potential (Rayner 2004). However, the ultimate technical and social outcomes of a technology are usually far removed from these initial visions (Williams 2006). These visions anticipate and influence the future but they cannot predict it; they reflect, rather, our *current* ideas — we cannot envision the world as future generations will see it (Grunwald 2014).

This is a challenge but also an opportunity for Responsible Innovation. Rather than understanding innovation as simply '*whatever happens to emerge from incumbent structures of interest, privilege, and power*' (Genus and Stirling 2018, 62), RI calls into question the '*narrative of inevitability*' (Stilgoe 2013) in the development trajectory of new science and technology and its societal impacts, good or bad. RI builds on an extensive body of enquiry showing that the technical and social outcomes of an emerging technology are not intrinsic but are patterned by a succession of choices as the technology is developed and adopted and becomes embedded in society (Williams and Edge 1996).

RI has been articulated around nanotechnology (Fisher and Rip 2013; Kjølberg and Strand 2011), artificial intelligence (Brundage 2016), information technologies (Jirotka et al. 2017), and synthetic biology (Macnaghten, Owen, and Jackson 2016). But beyond the generic lessons identified in retrospective studies of earlier technologies, there is a need to tackle the sociomaterial specificities surrounding quantum computing. Despite considerable uncertainty, it is possible to discern the outline of quantum computing on the horizon through the visions which define and shape it. The following sections explore these visions and framings, which we then unpack to discuss the implications for RI.

Quantum computing

There are many excellent expositions of quantum computing (see for example: (Aaronson 2013; Bernhardt 2019)); here we seek simply to give sufficient explanation to examine what quantum computing may imply for society. Briefly:

1. Quantum computing applies quantum phenomena, such as superposition and entanglement, to computation (DiVincenzo 2000; Ambainis 2014). Quantum computing holds the promise of speeding up or making possible solutions to *certain kinds* of computing problem, but is not *in general* faster than classical computing, except for specific computational problems (Aaronson 2008).
2. There is not one single form of quantum computer. Many physical systems showing controllable quantum effects, each with its own advantages and disadvantages, could enable quantum computing and its fundamental unit, the 'qubit' or quantum bit. Some of the most promising are: ion traps (the main approach adopted by NQIT), superconductors, photons, and qubits in solid-state materials (DiVincenzo 2000).
3. However, most physical qubits are vulnerable to environmental 'noise' and errors; building quantum computers for some of the most high-profile expected applications will require large numbers of error-corrected qubits. This is still far from being achieved and is a major research area in its own right.
4. Although large-scale, fault-tolerant 'universal', gate-based quantum computers may be years away, there is increasing interest in problems which might be solved by small quantum computers that already exist, or soon will do. These ideas have coalesced around what is known as 'Noisy Intermediate-Scale Quantum Computing' (NISQ), from an article by Preskill (2018).
5. The term 'quantum computer' is somewhat misleading. Computers are familiar artefacts as laptops, servers, smartphones etc. Quantum comput*ing*, our preferred term, will not replace

these forms of computer, at least as far as we can foresee. Quantum computing might be developed as 'Quantum Processing Units' (QPUs) co-processors (Britt and Humble 2017), and/or accessed over cloud-style services (Preskill 2018) — already possible in a limited way with the IBM Quantum Experience and its competitors.[3]

Meanwhile, non-quantum, 'classical' computing continues to develop in sophistication and speed (Bleicher 2018; Preskill 2018). This is not only a continuation of the increasing miniaturisation predicted by Moore's Law (Moore 2006) – but also through new models of computation, specialised architectures, and new kinds of materials and devices (Shalf 2020).

Visions of Quantum Computing

We identify three visions of quantum computing. In the first vision, we are on the threshold of an era of computing more powerful than anything that has gone before (Khan 2021). The second vision tries to identify practical implications of quantum computing in the short term (Preskill 2018). Thirdly, the discourse of 'quantum supremacy' is concerned with increases in speed for specialised problems, irrespective of real-world use-cases; the demonstration of quantum supremacy is said to herald a new era of quantum computing (Arute et al. 2019).

Capabilities far beyond the most powerful classical computers

There are classes of problem which even the most powerful, fastest classical computers cannot solve in a reasonable timeframe; quantum computing is expected to be able to help solve *a subset* of these problems (Aaronson 2008). Some quantum computing developers suggest that this will lead to '*a new computer technology era more powerful than anything that preceded it*' (Khan 2021), first in areas such as materials and drug development, and, later, transforming areas including machine learning[4] (Lloyd, Mohseni, and Rebentrost 2013; Biamonte et al. 2017; Dunjko and Wittek 2019) and natural language processing. This could have applications to defence, for example for improved target identification (Congressional Research Service 2021), and in many other application areas.

One capability which has drawn much attention is the potential to perform certain mathematically difficult tasks such as factorisation, impossible in a practicable timescale with large numbers using classical methods, but possible for quantum computing using methods such as Shor's algorithm (Shor 1999; Aaronson 2007). This requires capabilities far beyond what is currently available, but which, if implemented, would render many existing forms of encrypted communications insecure.[5] This would present an immediate problem for very high-value data communications or root-level public keys that must remain secure over many decades (National Cyber Security Centre 2020). However, researchers are already developing new forms of what is known as post-quantum cryptography (Bernstein 2009), seeking to develop cryptographic systems which are believed to be not vulnerable to this attack.

Quantum computing can be useful now, or soon will be

Despite important advances, however, flexible quantum computers on the scale of tens of thousands of qubits remain at least some years from achievement; the timescale, and whether it is even possible in principle, remains highly uncertain (Pritchard and Till 2016; Dyakonov 2019). Since such large-scale, error-corrected 'universal', gate-based quantum computers may be decades away, there is increasing interest in useful applications of quantum computing that are expected to be available in the near future (for example, (Wecker, Hastings, and Troyer 2015)). One example is 'Noisy Intermediate-Scale Quantum Computing' (NISQ) (Preskill 2018)**.** These devices are of the order of 50–100 qubits and are 'noisy': not fully error-corrected and are limited in the size of quantum circuits, or algorithms, that they can execute. (For a recent overview of progress, see (Bharti et al. 2021)). An innovator working with NQIT suggested that:

> *'there is an assumption that these devices would have to be very polished and very commercialised before they'd be able to be sold. … [but] there could be a market for this thing which is very unstable and very difficult to work with, but … is just about able to solve a problem which a normal computer couldn't.' – Interviewee LI5*

Useful tasks that such computing may be able to address near-term include:

Optimisation

Optimisation — such as the maximum or minimum value of some function[6] — in many cases is hard to do using classical computers (Mohseni et al. 2017). Optimisation underlies many practical applications and is also a key part of machine learning algorithms (Sra, Nowozin, and Wright 2012).

Quantum computing is not expected to be able to solve 'NP-Hard'[7] combinatorial optimisation problems such as the 'travelling salesperson' problem,[8] but is possible that they might be able to find good *approximate* solutions more quickly for some problems (Preskill 2018). However, it is by no means trivial to identify the optimisation problems for which quantum methods will provide an advantage over known non-quantum methods (Moussa, Calandra, and Dunjko 2020) – a reminder, again, of the uncertainty that surrounds quantum computing.

Quantum simulation

Another class of applications which may be amenable to NISQ or other early quantum computing methods is the wide field of quantum simulation (Johnson, Clark, and Jaksch 2014; Nielsen 2015). Simulation is an echo of Feynman's (1981) initial insight that to model quantum processes requires quantum mechanical devices. Modelling, or simulating, many physical processes at the sub-atomic level is a very difficult problem for classical computers that physicists have struggled with for decades, but seems to be a natural fit for quantum computing.

Simulation has important applications in areas such as atomic physics, quantum chemistry and cosmology ((Georgescu, Ashhab, and Nori 2014) provide a good review). Quantum chemistry has been mooted as the 'killer application' for quantum computing, including, possibly, efficient nitrogen fixation for fertiliser production; this occurs naturally and efficiently in nature but known industrial processes are energy-intensive (Reiher et al. 2017). Such quantum-enabled advances in chemistry are not likely to be reached in the 'NISQ era', but physicists do hope to use NISQ technology to learn interesting things about quantum dynamics, reminiscent of the way in which chaos theory developed rapidly from classical simulations with early computers in the 1960s and 70s (Preskill 2018).

But, in a resonant phrase, Preskill suggests that we '*probably lack the imagination to anticipate the most transformative discoveries which will flow from more powerful quantum simulators*' (Preskill 2018, 13) – expressing, in a form of 'de-facto' Responsible Innovation, the interplay of imagination and anticipation.

Quantum supremacy

The promise of quantum computing has recently been thrown into high profile by Google's announcement of a claim to 'quantum supremacy': the demonstration of a calculation on a quantum computer which would be beyond the capability of any classical computer (Harrow and Montanaro 2017; Arute et al. 2019). Google's quantum processor performed in 200 seconds tasks that their researchers estimate could take 10,000 years using a state-of-the-art supercomputer (Arute et al. 2019). The moment of 'quantum supremacy', assuming this is what has been achieved, has been said to be nothing less than '*a privileged time in the history of our planet*' (Preskill 2019); it has been demonstrated that quantum computing can do things that classical computers cannot

(Aaronson 2019), and — the most challenging part — can be controlled and made to do things as predicted by their designers.

Aside from unfortunate historical connotations of the word (Wiesner 2017), claims around ‘quantum supremacy’ have been contested (‘*the gloves are off*’ (Aaronson 2019)): researchers at IBM calculated that the world’s most powerful high-powered conventional computers could do similar calculations to Google’s quantum computer in 2.5 days, much faster than Google’s (Arute et al. 2019) estimate. Moreover, the calculation in this case is (probably) not very useful; it has been carefully chosen as something that quantum computing can do well but which is hard for non-quantum. Recall that quantum computing is not expected to replace or to be ‘supreme’ over non-quantum computing in general; meanwhile, non-quantum computers are also getting faster, partly as a response to advances in quantum computing; classical can ‘fight back’, but the direction of travel seems clear (Aaronson 2019).

From Visions to Responsible Innovation

These debates — about quantum supremacy, Google’s claim and IBM’s response; about what might be done with NISQ computing; and what might be possible with universal quantum computing and when — have largely been conducted in highly technical terms, and the trajectories towards universal quantum computing framed in terms of solving scientific and engineering problems.

However, the ‘*character and implications*’ (Williams 2006) of technologies are always open to question. This is clear in quantum computing, which requires not only advanced technology but also highly trained practitioners and has potential applications beyond what can currently be perceived. Despite the demonstration of ‘quantum supremacy’ for specialised tasks, the shape of future quantum computing performing ‘useful’ tasks at scale is still being formed. Part of NQIT’s role, participants in an RI workshop argued, was to participate actively in this discourse as a ‘*trusted source of information*’.

Even in technologies where the implementation is more advanced and apparently more certain, there are tensions between expectations of how a technology might be used and its intended sphere of operation. Fleck, Webster, and Williams (1990) analyse how 1980s visions of general-purpose robots as direct replacements for manual workers unhelpfully constrained understanding of their potential application in manufacturing; the anticipated development trajectory petered out or failed in the face of diverging user requirements.

It is easy in retrospect to identify trajectories from initial concept to adoption and widespread use, but this clarity is apparent only in hindsight (Pinch and Bijker 1984). Visions which attempt to project forwards not only risk being wide of the mark in practice but reify preconceived notions of what a technology ‘is’ and what it is ‘for’ — expectations which are the ‘*cause and consequence*’ of the ways in which technologies are developed, supported, and adopted (Borup et al. 2006).

Opening up visions

While the claims made for quantum computing need to be tempered by an understanding of the difficulties of realising it in practice, we expect in the medium- to long-term that at least some of its promises will be borne out, but — this is a crucial point for RI — probably not in the ways that we currently foresee. There are multiple visions and competing dynamics, opening up (Stirling 2008) different challenges and considerations. Major companies, research institutions, and nation-states vie for dominance. Choices throughout the development pathways of innovation are made in conditions of uncertainty and tension.

Applying an RI lens and building on these visions, in the terms of the Anticipate-Reflect-Engage-Act framework, it might be thought that we are still very much in the ‘Anticipation’ dimension, with perhaps a little scope for Reflection on what we know currently. Until quantum computing is in widespread use, it remains a ‘*social experiment*’ (van de Poel 2016). The already-difficult task of anticipating social consequences is obscured by layers of uncertainty; it is '*doubly fictional*' (Rip and Te Kulve 2008) still-imagined technical achievements from which plausible societal outcomes are then extrapolated.

Engagement is complex because of the conceptual challenges. It is hard for non-specialists to understand what quantum computing might actually be able to do (DiVincenzo 2017; Aaronson 2021b). Even for specialists, this is a subject of considerable debate. A public dialogue exercise in 2017 (Kantar Public 2018) found wide public familiarity with the word 'quantum', but little understanding of its application to quantum technologies: unsurprisingly, participants were most positive about applications with potential to benefit individuals and society and were wary of a quantum technologies 'arms race'. Dialogue remains essential to RI, however, both as '*the right thing to do*' (Stirling 2008) and to avert the risk that some compelling conception of quantum, positive or negative, will take hold and fill this space in the public imagination (Wagner et al. 2006).

The uncertainty and difficulties in anticipating the future potential and specific applications of quantum computing do not mean that RI has nothing to say or that there is nothing that can be done in the 'Act' dimension. The aim of RI is not to 'tick box' instrumental issues which might be raised by quantum computing but to engage in the process of anticipating and reflecting on the shape and framings of these technologies as they emerge. In our view, RI can make valuable contributions, not based on any attempt at *predicting* the future trajectory but from analysing these visions as '*sociotechnical imaginaries*' (Jasanoff 2015) which shape the emerging forms of quantum computing.

Imaginaries of quantum computing

One vision of quantum computing is of a new industrial revolution '*at an even larger scale than anything we have previously experienced*' (Khan 2021). A recent prospectus for a quantum computing company public offering suggests: '*Computers that utilise the power of quantum mechanics could provide revolutionary breakthroughs in human health and longevity, climate change and energy production, artificial intelligence, and more*' (IonQ 2021).

We could call this the 'heroic' early vision; at the current stage of knowledge, it is hard to draw a line between '*defensible optimism*' and exaggeration (Aaronson 2021a). The strong claims of quantum computing as the 'next big thing' (Rayner 2004) are counterbalanced by acknowledgements that the list of mathematically intractable problems currently known to be solvable by quantum computing is not a long one (DiVincenzo 2017). Unfulfilled early promises could lead to a 'quantum winter' (The Economist 2018). In either eventuality – or some more nuanced, complex mix of outcomes – these visions shape the '*assemblages of materiality, meaning, and morality*' (Jasanoff 2015) and are constitutive of, as well as reflective of, forms of social life. RI might explore how these visions may mobilise large investments and direct them towards some fields rather than others.

A more negatively figured potential of quantum computing is the risk of 'breaking the Internet' — rendering vulnerable existing forms of encryption — using Shor's algorithm or similar (Biever 2013) (alternatively, '*giving governments more power to surveil their citizens*' (Aaronson 2021a)). This risk is real, but should be an in-principle solvable problem, although not without continuing challenges. Nevertheless, this does have a significant interest for RI: we suggest that post-quantum cryptography (Bernstein, 2019), by anticipating and responding to a problem, is implementing 'de-facto' anticipatory governance elements of RI.

However, actually building a quantum computer that presents this risk — or that solves more socially-useful problems — is still very challenging, as we have repeatedly emphasised. These challenges are framed more as 'engineering' than as 'science' by a senior NQIT researcher:

> *'my take on it is, the physics, the science, has largely been done, so, as far as the physicists would believe, it's engineering' – LD2*

but, as we have stated, simply 'scaling up' is uncertain and with plenty of potential surprises; some argue that it is impossible (Dyakonov 2019) or, possibly, according to an NQIT researcher, failure could call into question quantum mechanics as a scientific paradigm:

> *'although we have absolutely no reason to think that at some point as you try and build a bigger and bigger version of a quantum computer anything should go wrong, like you should just be able to scale it up, … it's very difficult to be totally sure … if it didn't work out, that would mean something in the foundations of quantum theory was wrong … we're really putting that to the test' – LR8*

Conversely, quantum computing has important implications for physics:

> *'if one builds a quantum computer, not only can you solve societal problems, but you can also start to study new regimes of physics which you cannot do in any other way' – LD4*

Meanwhile, the discourse of NISQ is raising hopes of what might be possible with quantum computing in the near- to mid-term. What is interesting as a sociotechnical imaginary is the way in which the 'material' (Jasanoff 2015) — algorithms as well as hardware — is slowly coming together with 'the social'. If/when NISQ devices are adopted outside the specialised quantum research communities, it can be expected that the set of real-world applications will deepen as users adapt, appropriate, and try things out with the available technology in practices of mutual shaping or *innofusion* (Fleck 1993; Williams and Edge 1996). Indeed, Preskill (2018) suggests that NISQ might provide testbeds to in turn accelerate the development of quantum algorithms.

Arms race or the common good

Debates about the achievement of quantum supremacy, technically defined and demonstrated experimentally though not particularly useful outside quantum computing research, sit alongside broader visions of what supremacy in QC might entail. 'Supremacy' in other contexts is framed in terms of military superiority or economic dominance by nation states, tending to orient scientific and technological advances towards national or company goals rather than the common good of humanity.

Similar discourses surrounded, for example, the Japanese Fifth Generation Computer Systems Project (FGCS) in the 1980s. Intended for AI as a public good, FGCS provoked fears in the United States of Japanese technological world domination (Feigenbaum and McCorduck 1983). Widely seen as a failure in *Western,* commercial terms, re-framed as a contest between nations (Garvey 2020), neither FGCS nor competing national initiatives succeeded in their broader aims of Artificial Intelligence (AI). In a pertinent turn of history, the subsequent 'AI Winter' has now given way to a new AI 'arms race', this time with China as the antagonist to the USA.

We see parallels between the history of FGCS and the emerging history of quantum computing. Following the logic of supremacy, quantum technologies are becoming a central part of national and supra-national economic strategies.[9] Narratives of new technologies are largely formed through strategy documents and roadmaps which produce and reproduce established framings (Marris and Calvert 2020); examples such as the UK National Strategy and the Roadmap for quantum technologies (UK National Quantum Technologies Programme Strategic Advisory Board 2015b, 2015a) are not passive descriptions, but performatively construct the concept of quantum technologies and what they are 'for'.

Conclusions

The increasing emphasis on Responsible Innovation as a core aspect of scientific and technological development makes this a privileged time to consider RI applied to a core emerging technology.

When the research on which this paper is based commenced, quantum computing was expected to be several years, possibly decades, from realisation. The NQIT Hub aimed to progress the underlying elements of scalable quantum computing, and to contribute to quantum information theory and other quantum technologies. Production of a large-scale, fault-tolerant quantum computer was not expected in a near-term timescale and is still some years distant. However, quantum comput*ing*, using quantum effects to do interesting and useful computation, has developed in other ways, with new insights and new framings, so that the shape of the technology envisaged at the start of our research is somewhat different from the ways it is understood now.

This shift – in a relatively short space of time – demonstrates the importance of RI's iterative, responsive approach. Applying RI through the AREA Plus framework is not once-and-for-all: the parameters are changing even as we attempt to delineate them.

The trajectories of these technologies are hard to perceive: some are near-term, some are barely visible on the horizon, others are speculative. Solutions to some specific computing and optimisation problems, quantum machine learning, new forms of simulation of drugs and materials, and risks and opportunities for secure communications, with applications in fields such as medicine, logistics, and finance: any and all of these, and others that have not yet been imagined, are likely to engender social transformations. These transformations arise not only from specific affordances of the technology, but from the interplay of society and technology, from the ways in which the technology is imagined, adopted, and co-designed in use, from its governance and its availability.

Faced with this complex web of interests and a highly uncertain trajectory of innovation (Fleck, Webster, and Williams 1990), RI seeks to contribute to a '*proper embedding*' (von Schomberg 2013) of quantum computing in society, recognising its anticipated applications as '*sociotechnical imaginaries*' (Jasanoff 2015). Responsible Innovation can actively engage in these framings, anticipating and reflecting on possible futures. The point is not to predict or only interpret the future in various ways, but to explore, prepare and respond to it**.**

Notes

1. https://ec.europa.eu/programmes/horizon2020/en/h2020-section/responsible-research-innovation
2. https://epsrc.ukri.org/research/framework/area/
3. https://quantum-computing.ibm.com/
4. https://www.quantummachinelearning.org/qtml2021-program.html
5. https://en.wikipedia.org/wiki/Shor%27s_algorithm
6. https://en.wikipedia.org/wiki/Mathematical_optimization
7. https://en.wikipedia.org/wiki/NP-hardness
8. https://en.wikipedia.org/wiki/Travelling_salesman_problem
9. The UK press release about the recent 'New Atlantic Charter', which is notably less global in outlook than the original of 1941, specifically mentions quantum technologies alongside AI as part of a USA-UK science and technology partnership: https://www.gov.uk/government/news/uk-and-us-agree-to-strengthen-ties-in-science-and-technology

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